A Phase-shifting Zernike Wavefront Sensor for the Palomar P3K Adaptive Optics System

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ABSTRACT

A phase-shifting Zernike wavefront sensor has distinct advantages over other types of wavefront sensors. Chief among them are: 1) improved sensitivity to low-order aberrations and 2) efficient use of photons (hence reduced sensitivity to photon noise). We are in the process of deploying a phase-shifting Zernike wavefront sensor to be used with the real-time adaptive optics system for Palomar. Here we present the current state of the Zernike wavefront sensor to be integrated into the high-order adaptive optics system at Mount Palomar's Hale Telescope.

Keywords: adaptive optics, wavefront sensing.

1. INTRODUCTION

The world doesn't suffer from a lack of wavefront sensors. Sensors which measure wavefront are common in the lab and range from the simple and robust (think shear plate interferometer) to the complex and sensitive (think phase-shifting interferometer). Adaptive optics systems which measure the corrugated wavefront errors induced by the Earth's atmosphere and correct these errors to restore near perfect imagery put additional requirements on classic wavefront sensors. They must work with broadband starlight, they must sense very fast to keep up with the ever changing atmosphere, and they must be robust in order to be relied upon for routine observations.

In this paper we present a new variety of wavefront sensor which meets these requirements: sensitive, robust, broadband operation and fast. This sensor is also very photon efficient, and is therefore more sensitive. It is also advantageous in that it makes a direct measurement of the wavefront (not the wavefront curvature or slope) and is therefore less susceptible to error propagation. Here, we summarize the operation of the wavefront sensor, describe our implementation in both opto/mechanics as well as electrical and software. Our plan is to integrate this wavefront sensor with the Palomar Adaptive Optics System (P3K) in order to demonstrate its operation on the sky.

2. DESCRIPTION OF THE WAVEFRONT SENSOR

We have described the physics and architecture of this wavefront sensor in great detail in another paper [1], so here we provide a high-level overview of the key components. It is based in the phase-contrast method developed by Fritz Zernike [2,3,4,5]. Zernike's original concept was to induce a static phase shift ($\pi/4$ or $-\pi/4$) at the core of a point-spread function intermediate between the input pupil plane and the output pupil plane. This static phase shift has the effect of transforming a phase error in the input pupil into an intensity signal in the output pupil. This simple optical element makes it possible to image phase objects which are otherwise transparent (like biological specimen, for instance). Dicke first proposed using this method for visualizing atmospheric phase aberrations [6]. A more detailed description of the underlying physics and mathematics can be found in the literature [7,8,9,10,11]

Our modification to this method was: 1) implement this in a reflective system to operate broad-band, 2) make the phase step at the core of the PSF adaptive and variable such that it can be made to switch between $+\pi/4$ and $-\pi/4$ in short order. These modifications make the system simple and robust. The implementation is illustrated below in Figure 1. The input pupil is located at the front focal plane of a parabola. Upon reflection, the pupil is imaged to infinity, and the image is at the parabola focal plane. In this focal plane is located the reflecting phase-shifting element. Upon reflection, the beam is re-collimated by the parabola, and forms a real image of the input pupil at the parabola focal length. This pupil is then imaged to the final detector with a relay that also shrinks the exit pupil image size.

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Updated 25 June 2012

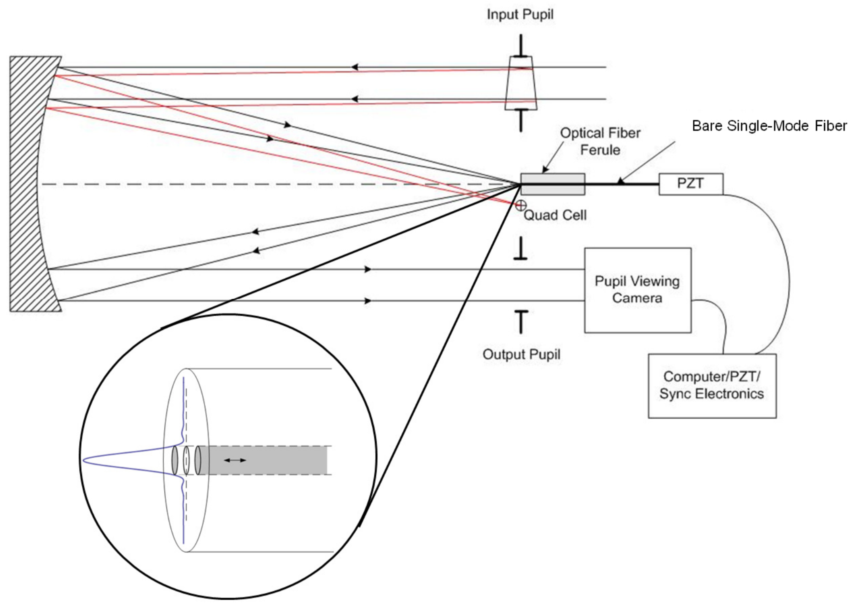

Figure 1. The functional layout of the system is shown in the diagram above. Light enters though the input pupil in the upper right. Upon reflection from the parabolic mirror, the pupil is imaged to infinity, but an imaged at the focal point of the parabola. At this focal point, a reflective phase-shifting element is located. The core of this image is phase shifted with respect to the Airy rings. Upon a second refection from the parabolic mirror, a real image of the pupil is formed again. The PZT secured to the bare, cleaved single-mode fiber induces the phase-shift on the PSF. The phase-shift is done synchronously with the image acquisition.

The heart of the reflective Zernike wavefront sensor is shown below in Figure 2. It consists of a fine mechanical assembly: a capillary tube with a small inner orifice. The end face of this capillary is end polished and coated with a reflective metal coating. Internal to this capillary is placed a single mode fiber, the end-face of which has been cleaved to be flat, and also coated with the same reflective coating to be reflective. The single mode fiber is used for it's mechanical properties: the outer diameter is controlled to very high uniformity in the outer diameter and with very tight tolerances on the error in the diameter. This single mode fiber is simply guided by the inner capillary but is otherwise free to move. The far end of the fiber is gripped in a clamping mechanism and attached to a PZT. Very fine translations of the filament are permitted by the PZT which has a range of twelve microns for a change of 100 volts. Thus changes on the order of +/- $\lambda/4$ can be had for a voltage change of only 2.5 V. (The coarse positioning of the fiber is accomplished by an in-line linear stage.)

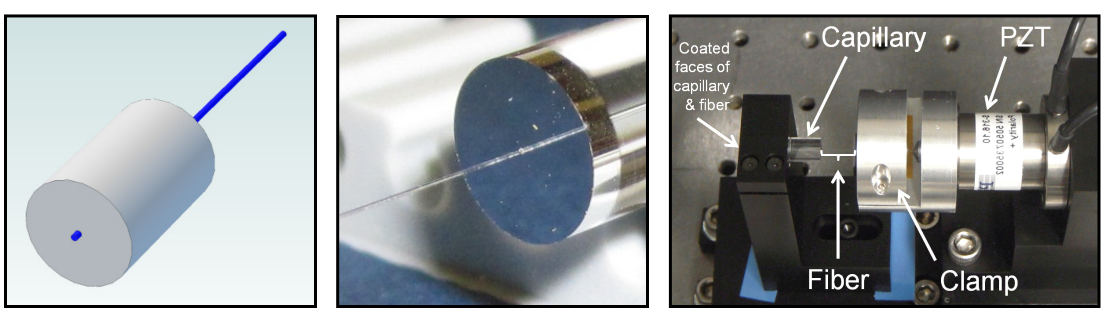

Figure 2. The diagrams above illustrate the details of the phase-shifting element. The central hole of the capillary tube is well controlled. The end face of this capillary tube is optically polished to be flat and normal to the central hole. It is subsequently coated. The single mode fiber (shown in blue on the left) is used for its mechanical properties: well controlled outer diameter, stiff, and can be cleaved to produce a mirrored surface. It is inserted into the center of the capillary, where it is supported by also free to move along the length of the capillary. A PZT actuator is secured to the single mode fiber via a clamp, thus very fine motions of the filament can be accomplished with small voltages.

3. OPTO/MECHANICAL HARDWARE IMPLEMENTATION

This same opto-mechanical relationship between pupil and image planes was held when implementing this wavefront sensor for the Palomar system. However, we had the additional constraint that the wavefront sensor had to be done in such as way as to have little to no impact on the routine operation of the system: the existing Shack-Hartman wavefront sensor would remain, and our Zernike wavefront sensor would not otherwise interfere with routine operation. A detailed description of the Palomar high-order adaptive optics system is described in the literature.

We also had to fit within a very tight volume constraint. We were allocated space between the final pick-off beamsplitter and before the science instrument. This location was very snug, and placed us very closed to critical components of the existing system. However, with some optical origami we were able to get this system to fit within the allowable volume.

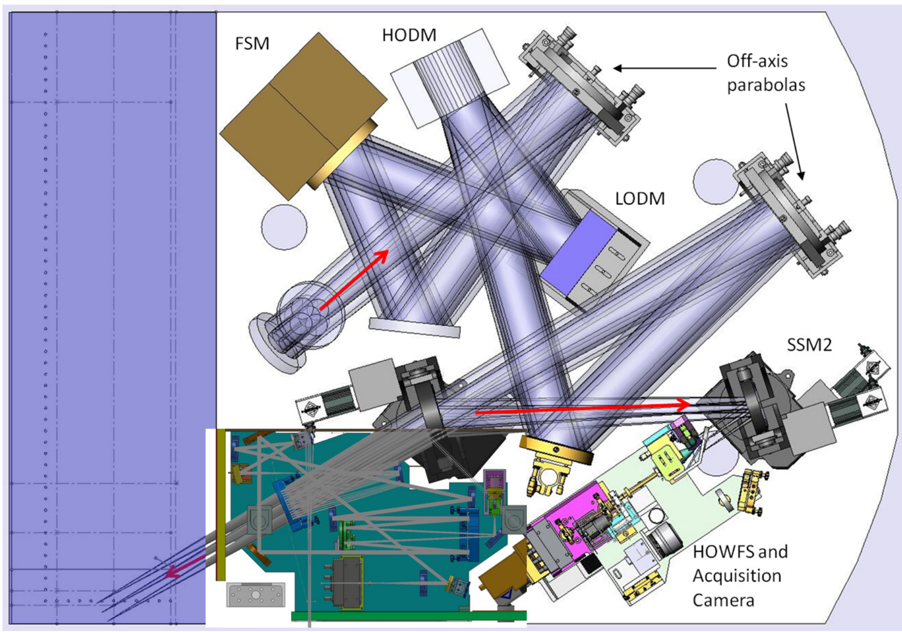

Figure 3. The Zernike wavefront sensor integration with the Palomar adaptive optics system is shown above. The adaptive optics system is shown in the central part of the diagram. The Zernike wavefront sensor is added after the pick-off beamsplitter for the Shack-Hartman wavefront sensor. It fits within the small rectangular area after the P3K adaptive optics system and before the science instrument. It will be assembled and tested on a small breadboard which fits in this volume and integrated as a whole.

The pick-off beampslitter directs the on-axis beam first to a fold mirror and then to an off-axis parabolic mirror. This parabolic mirror collimates the beam and creates a real image of the telescope pupil. The effective focal length of the telescope is located at this pupil location as well, making it a telescentric telescope. The fold mirrors feed this beam into the telescope which is composed of a parabolic primary mirror and a slow secondary mirror. At the focal point of this telescope system is located the same phase-shifting element used in the lab. Traversing back through the telescope optics from this focal plane element, the exit pupil is again formed at the effective focal length of the system, which is quite long. A couple of oversized fold mirrors are required in order to bring this output pupil image close to the final imaging camera. A small relay then images this pupil onto the wavefront sensor detector array.

The mechanics are made to be non-adjustable save for manual clocking and tilts accomplished via shimming. Optics and mechanics are mounted onto a small breadboard that allows for stand-alone testing before installation as a whole integrated system into the P3K system.

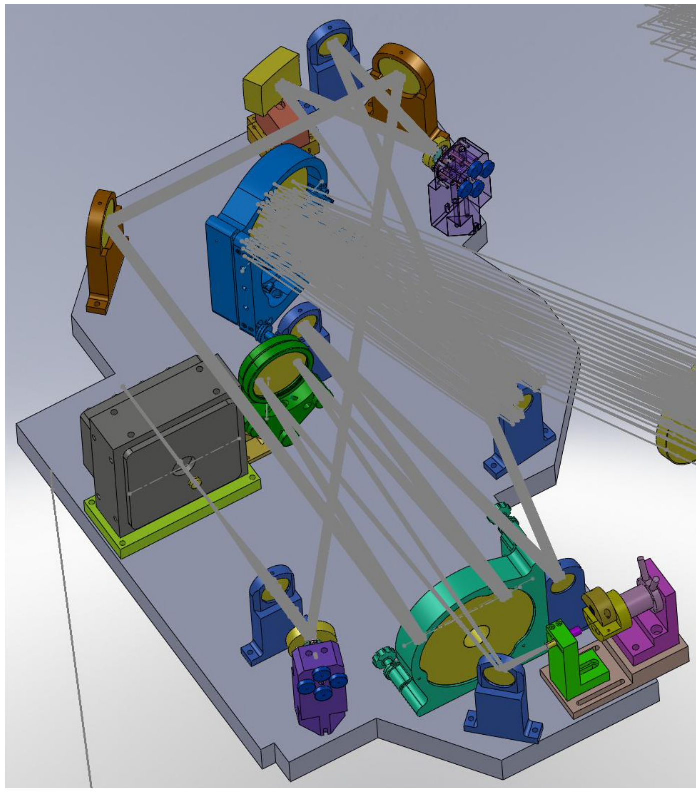

Figure 4. The optical layout of the stand-alone breadboard is shown in the image above. Light for wavefront sensing is picked off from the main beamsplitter (large blue mount in the upper center part of the diagram). This light is folded and re-collimated by the rectangular off-axis parabolic mirror. The pupil is formed at the location of the purple mount in the upper right. Light is redirected towards the telescope, and then to the phase shifting element in the lower right. At the output of the telescope, the light is directed towards the fold mirrors and then back to the WFS Camera (gray box on the left hand side).

4. ELECTRICAL/SOFTWARE IMPLEMENATION

Interfacing to the Palomar adaptive optics system requires careful attention to requirements for real-time communication. We start by adopting as much of the physical layer in the AO implementation as possible. This ensures compatibility and a high level of confidence that the hardware will operate as required. The description below essentially follows the path of the data from the wavefront sensor camera to the point where it is integrated into P3K system.

The wavefront sensor camera is a CCD39 from e2v. It is a four port camera with 40x40 pixels per port. This camera previously served as the wavefront sensing camera for the low-order adaptive optics system at Palomar. It can sample at speeds up to 2 kHz, with very low read noise and dark current. The sensor has its own set of electronics (commonly known as 'Little Joe' electronics from Scimeasure Analytical Systems, Inc.). Data is transmitted to the Zernike WFS computer via camera link protocol but implemented as a fiber-optic Tr/Rx pair by EDT, Inc.

Our computer is a HP 4800 Workstation operating with Suse Linux, enterprise edition. The fast computing will be done with the same Nvidia GPU cards as used the by AO system. The reconstruction algorithm is very simple (a difference and scaling operation), and does not require extensive compute resources. However, having a common hardware and software development environment for doing these operations makes work efficient. We plan on using the extensive computing power to do future wavefront estimation improvements. The computer is used to estimate the residual phase error from the ZWFS camera, from this phase error, the new values for the low-order and high-order deformable mirrors (LODM and HODEM respectively) are generated. These results are then sent PCO where they are integrated.

For the communications, we use a Quadrics network, again adopted wholesale from the Palomar system. A single Quadrics network card is installed in our machine, and interfaces to the rest of the system via the Quadrics QsNet 16 port switch. The switch relays data to PCO where the instrument control occurs. The HODM and LODM offsets are integrated into the control scheme with their own separate gain values. In this way, the ZWFS signals can be integrated into the control system with very little impact to the current operation of the system.

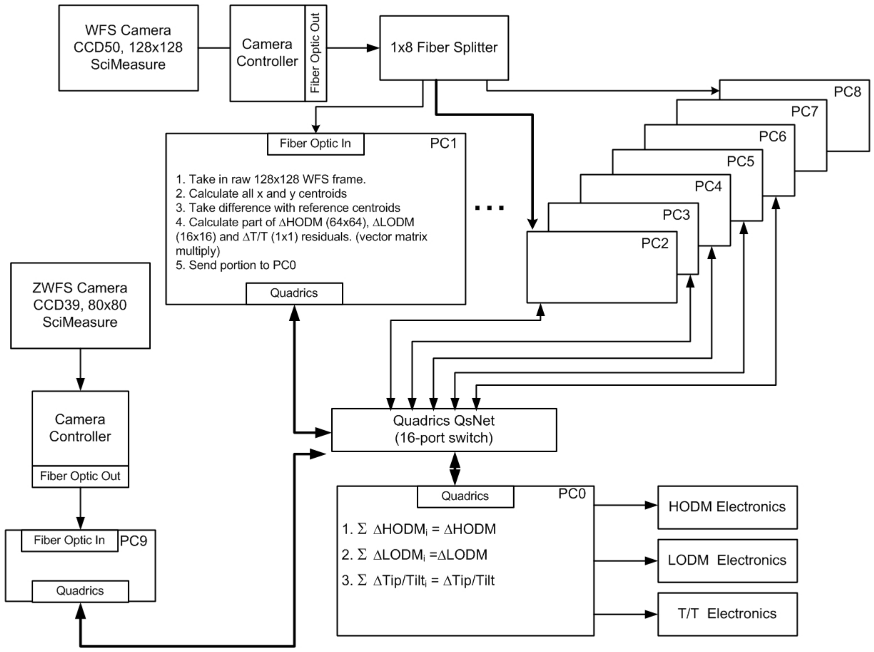

Figure 5. The above illustration shows the hardware architecture of the Zernike Wavefront Sensor. The Zernike specific hardware is on the left hand side of the drawing. It shows the ZWFS Camera, the signal from the camera controller, from the controller to the ZWFS computer (PC9). In this PC the measured data is used to form an estimate of the wavefront phase, and from this low-order and high order offsets (LODM and HODM respectively). These offsets are then sent to PC0 via the Quadrics Network. Realtime software in PC0 is used to integrate the HODM and LODM offsets from ZWFS into the instrument control.

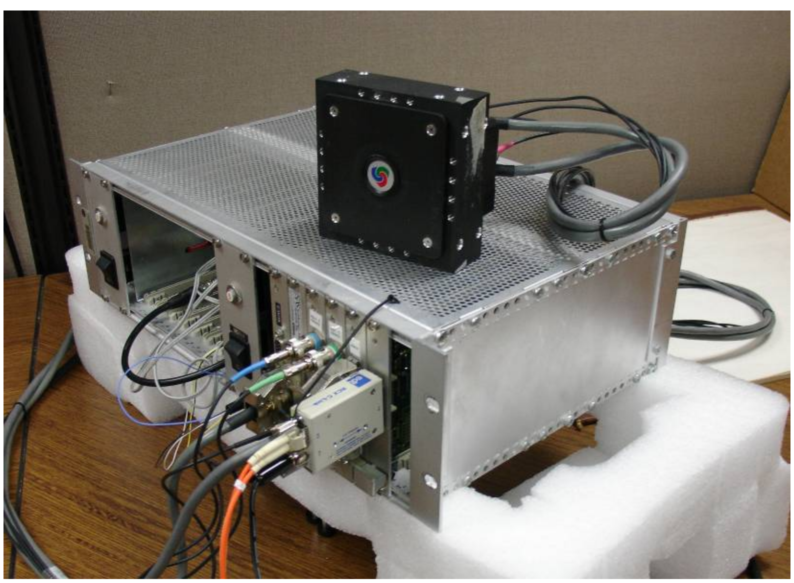

Figure 6. An image of the wavefront sensing camera used for in this experiment. The camera is uses a CCD39 from e2v, that is driven by readout electronics from Scimeasure Analytical Systems, Inc. The interface to the PC9 ZWFS computer is via the camera link protocol implemented over the fiber optic communication link (orange fibers shown in center bottom).

5. FUTURE WORK

The ZWFS hardware is currently being procured, aligned and integrated. We've secured the wavefront sensing camera, the control computer, with its GPU card and the fiber-optic communications interface. We have secured the parabolic primary mirror and are in the process of procuring and coating the other optics in the system. We have also fabricated a proto-type breadboard in order to do a testfit of the hardware into the system. Our plan is to fully integrate, align and test this hardware by the end of the September 2012. We plan on deploying this instrument to Palomar next year.

6. ACKNOWLEDGEMENTS

This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This work was supported by JPL's Research and Technology Development Fund.

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